

## The socio-technical dynamics of low-carbon transitions

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# Reviewing the socio-technical dynamics of low-carbon transitions

Revised Review paper for *Joule*

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**Summary** Effective mitigation of climate change will require far-reaching transformations of electricity, heat, agricultural, transport and other systems. The energy studies and modelling research that so often dominates academic and policy debates provide valuable insights into these transitions, but remain constrained by their focus on rational decision-making and their neglect of non-linear dynamics and broader social processes. This review paper describes insights from a complementary socio-technical approach that addresses the interdependent social, political, cultural, and technical processes of transitions. Focusing on the ‘Multi-Level Perspective’ (MLP), transitions are conceptualized as arising from the alignment of processes within and between three analytical levels: niche-innovations, socio-technical regimes and the socio-technical landscape. This analytical framework is illustrated with a case study of the German electricity transition and used to appraise low-carbon transitions in several other sectors. We end by articulating four lessons for managing low-carbon transitions.

Keywords: energy transitions; socio-technical approach; multi-level perspective

## 1. Introduction

Effective mitigation of climate change will require simultaneous transitions towards low-carbon electricity, heat, agricultural, transport and in other systems. The energy studies and modelling approaches that dominate academic and policy debates provide valuable insights into the nature and characteristics of these transitions, but also have several important limitations.<sup>1</sup>

Firstly, such studies have a limited representation of the range of actors involved (mostly firms, consumers and exogenous policymakers) and the manner in which they make decisions (mostly rational, optimizing). Secondly, transitions are conceptualized as tame processes, consisting of the steady deployment of low-carbon technologies represented via smooth diffusion curves. Thirdly, IAMs in particular optimize on one dimension (social surplus or cost), identifying optimal or ‘first-best’ pathways, even if these include technologies that are socially controversial or not yet feasible, like bio-energy with carbon capture and storage.<sup>2</sup>

Following the 2015 Paris agreement, climate change debates are moving from abstract modelling towards real-world implementation of solutions. This requires the development of more realistic and situated understandings of low-carbon transitions that can alleviate the above limitations. Firstly, transitions should be conceptualized as involving a wider range of actors, which include not only firms and consumers, but also civil society groups, the media, local residents, city authorities, political parties, advisory bodies, and government ministries.<sup>3</sup> The actions of these groups are guided not only by important and well-documented cost-benefit calculations, but also by entrenched beliefs, conflicting values, competing interests, unequal resources and complex social relations.

Secondly, low-carbon transitions are not only about the market diffusion of new technologies, but also about changes in user practices, cultural discourses, and political struggles. Transitions are therefore not tame, but disruptive, contested and non-linear processes. *Disruptive*, because they threaten the economic positions and business models of some of the largest and most powerful industries (e.g. oil, cars, electric utilities, agro-food), which are likely to protect their vested interests.<sup>4</sup> *Contested*, because actors disagree about the desirability of different low-carbon solutions and often resist their implementation (e.g. onshore wind turbines, carbon capture and storage). *Non-linear*, because climate change policies and low-carbon innovations can experience setbacks, accelerations or cycles of hype and disappointment (e.g. current climate policies in the UK, USA and Australia).<sup>5</sup>

Thirdly, low-carbon transitions require complex negotiations and trade-offs between multiple objectives and constraints, including cost-effectiveness, equity, social acceptance (legitimacy), political feasibility, resilience and flexibility.<sup>6</sup> The uncertain, long term benefits of carbon mitigation lacks salience and need to be aligned with other objectives to gain stakeholder support.

Fourthly, low-carbon transitions are goal-oriented or ‘purposive’ in the sense of addressing the *problem* of climate change. This makes them different from historical transitions which were largely ‘emergent’, with entrepreneurs exploiting the commercial *opportunities* offered by new technology.<sup>7 8</sup> Since climate protection is a public good, private actors (e.g. firms, consumers) have limited incentives to address it owing to free-rider problems and prisoner’s dilemmas. This means that public policy must play a central role by changing economic frame conditions (via taxes, subsidies, regulations, standards) and supporting the emergence and deployment of low-carbon innovations. However, substantial policy changes involve political struggles and public debate because: “[w]hatever can be done through the State will depend upon generating widespread political support from citizens within the context of democratic rights and freedoms”.<sup>9</sup> These considerations reinforce the point that low-carbon transitions involve interactions between multiple societal groups.

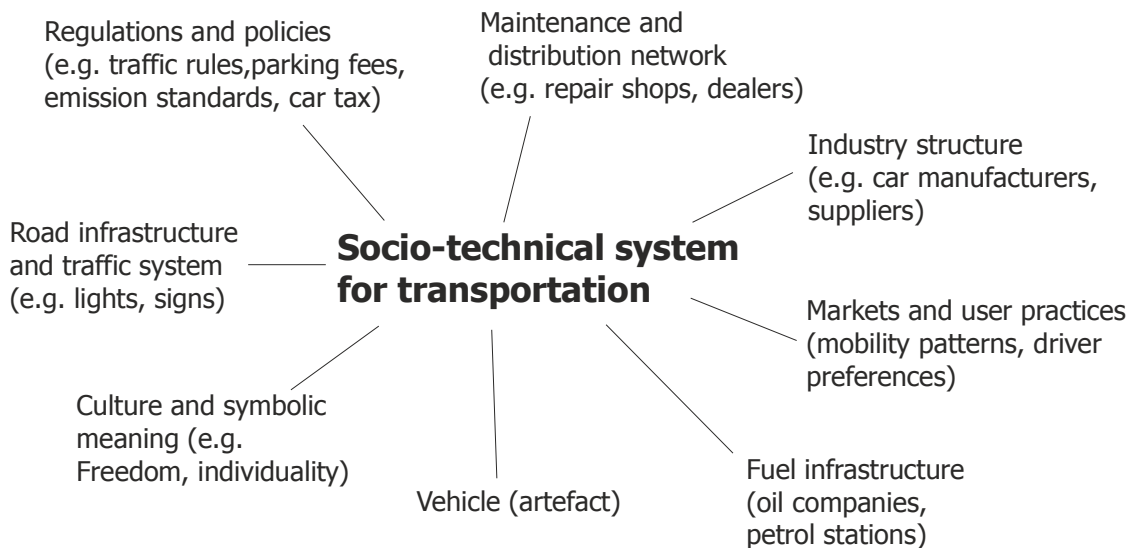
To address these challenges, this Review builds on calls<sup>10 11</sup> to include more social science in climate mitigation research and presents a ‘socio-technical’ framework for understanding and managing low-carbon transitions. This framework has guided work within the Sustainability Transitions Research Network (<http://www.transitionsnetwork.org/>), which has more than 1300 members globally. The following section introduces the sociotechnical perspective, while Section 3 illustrates these ideas with a case study of the German electricity transition. Section 4 reflects on the status of low-carbon transitions in different sectors, while Section 5 draws some lessons for managing those transitions. Section 6 concludes.

## 2. Levels and phases in sociotechnical transitions

The Multi-Level Perspective (MLP) argues that transitions entail major changes in the ‘socio-technical systems’ that provide societal functions such as mobility, heat, housing and sustenance.<sup>12</sup> These

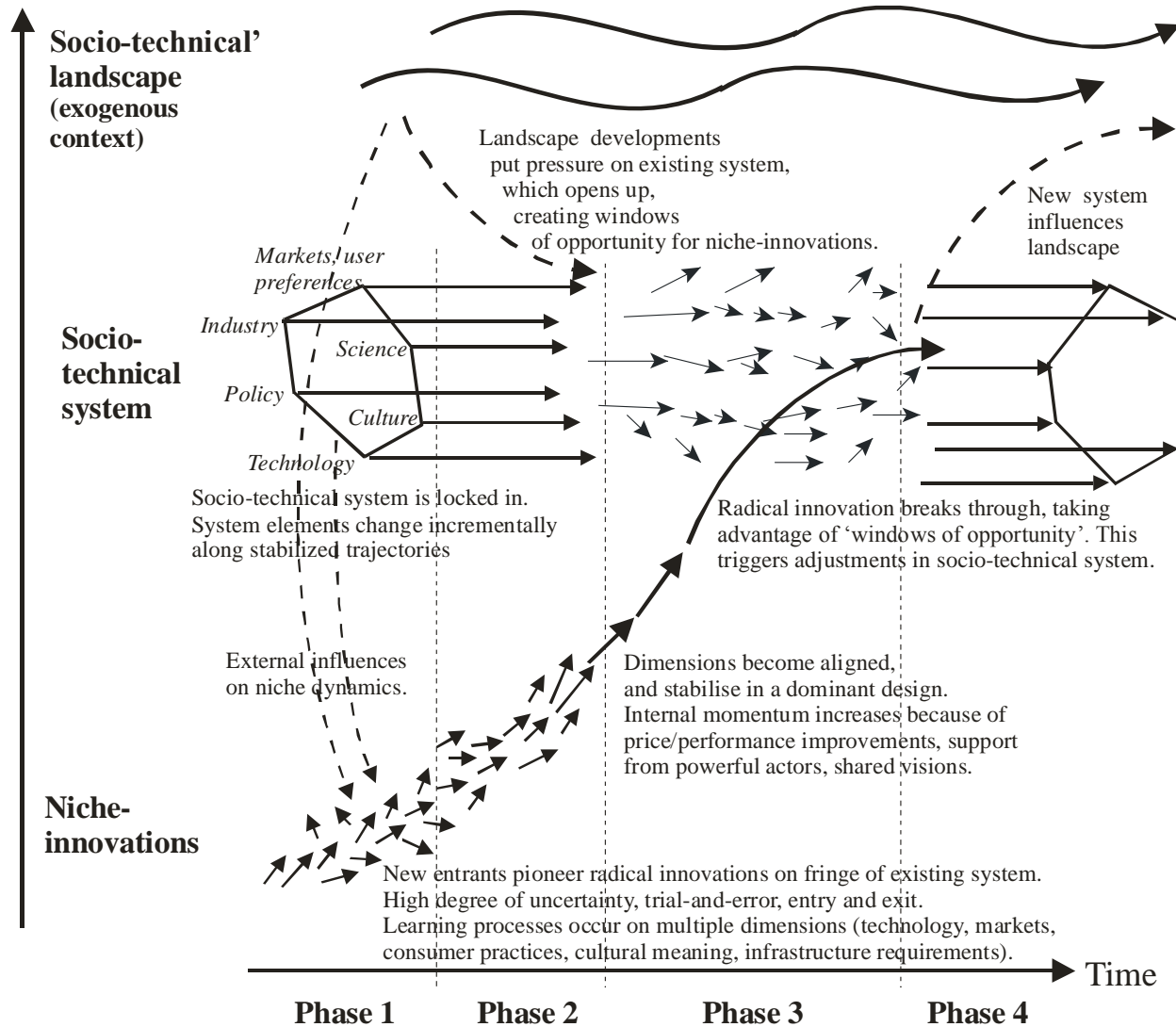
systems consist of an interdependent and co-evolving mix of technologies, supply chains, infrastructures, markets, regulations, user practices and cultural meanings.<sup>13</sup> Sociotechnical systems develop over many decades, and the alignment of these different elements leads to path dependence and resistance to change. Existing systems are maintained, defended and incrementally improved by incumbent actors, whose actions are guided by deeply entrenched rules and institutions – termed ‘socio-technical regimes’. Figure 1 provides an example of the car-based transportation system, which in most Western countries accounts for 80-85% of passenger-kilometers. This system is sustained by formal and informal institutions such as the preferences and habits of car drivers; the cultural associations of car-based mobility with freedom, modernity and individual identity; the skills and assumptions of transport planners; the technical capabilities of car manufacturers, suppliers and repair shops; and so on.<sup>14</sup>

*Figure 1: Schematic figure of socio-technical system of auto-mobility*



The MLP argues that sociotechnical transitions involve interactions between the incumbent regime, radical ‘niche-innovations’ and the ‘sociotechnical landscape’. Niche-innovations are emerging social or technical innovations that differ radically from the prevailing sociotechnical system and regime, but are able to gain a foothold in particular applications, geographical areas or markets (e.g. the military), or with the help of targeted policy support. The socio-technical landscape refers to broader contextual developments that influence the sociotechnical regime and over which regime actors have little or no influence. Landscape developments comprise both slow-changing trends (e.g. demographics, ideology, spatial structures, geopolitics) and exogenous shocks (e.g. wars, economic crises, major accidents, political upheavals). The MLP’s key claim is that transitions come about through the alignment of processes within and between the three levels, as depicted in Figure 2. Hence, to fully *explain* transitions it is necessary to identify these processes and the complex interactions between them; while to effectively *shape* the speed and direction of transitions it is necessary to influence several of these processes simultaneously.

Figure 2: Multi-level perspective on sociotechnical transitions (adjusted from ref. 13)



The MLP distinguishes four phases in these decades-long transition processes.<sup>15</sup> In the first phase, radical innovations emerge in niches, on the fringe of existing regimes. Innovator networks are unstable, uncertain, experimental, and fragile, propagating different design options - many of which will fail.

In the second phase, the innovation enters small market niches that provide resources for further development and specialization. The innovation develops a trajectory of its own, with a dominant design emerging and with the expectations and associated rules beginning to stabilize.

In the third phase the innovation breaks through more widely and begins to compete head-on with the established regime. On the one hand, this process depends upon drivers internal to the niche such as price/performance improvements, scale and learning economies, the development of complementary technologies and infrastructures, positive cultural discourses and support from powerful actors. On the other hand, the incumbent regime begins to destabilize as a consequence of

persistent internal problems (e.g. urban air quality), landscape pressures (e.g. rising oil prices) or a combination of the two, thereby creating windows of opportunity for niche-innovations. Table 1 summarizes some typical drivers of niche momentum, along with typical sources of tension within regimes. Struggles between niche-innovations and existing regimes typically play out on multiple dimensions, including: economic competition between old and new technologies; business struggles between new entrants and incumbents; political struggles over adjustments in regulations, standards, subsidies and taxes; and discursive struggles over problem framings and social acceptance.

The fourth phase is characterized by regime substitution, with the widespread adoption of the new innovations being accompanied by far-reaching adjustments in infrastructures, policies, industrial and market structures, lifestyles and views on normality. The new regime becomes institutionalized and increasingly taken-for-granted.

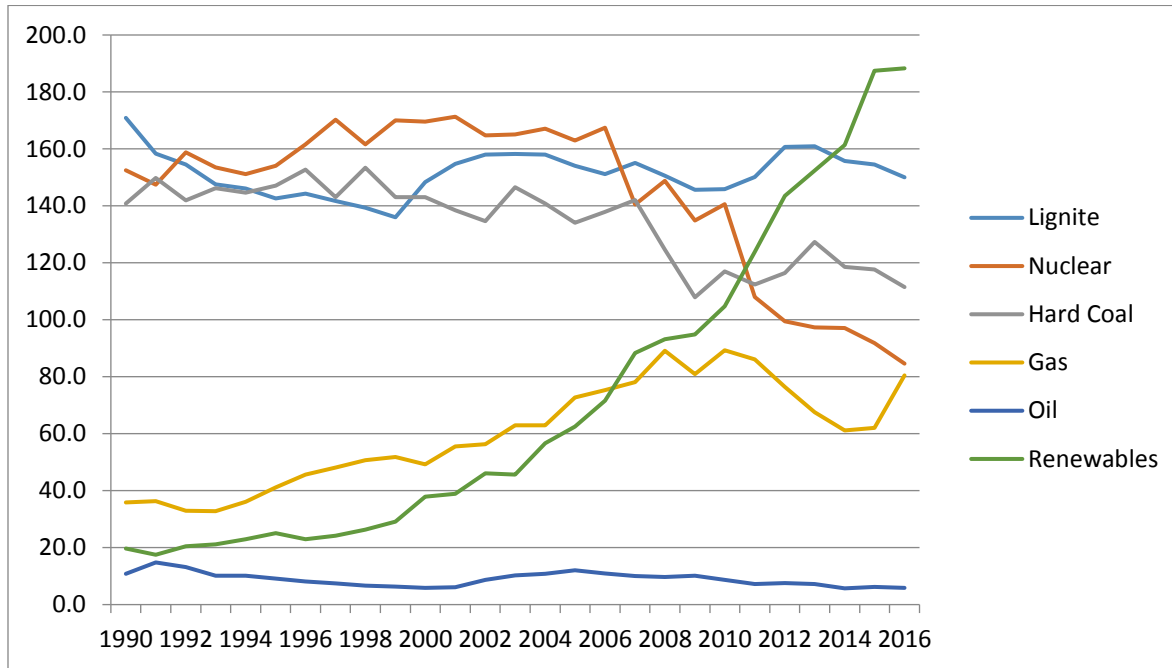
*Table 1: Drivers of niche momentum and regime tensions*

	<b>Endogenous niche momentum</b>	<b>Regime tensions</b>
<b>Techno-economic</b>	Price/performance improvements as a result of R&D, learning-by-doing, scale economies, complementary technologies, and network externalities.	Technical failures, disruption of infrastructures, accumulating negative externalities (e.g. CO <sub>2</sub> emissions).
<b>Business</b>	New entrants or incumbents from other sectors are more likely to drive radical innovation than traditional incumbents. Their success may lead to ‘innovation races’ when other firms follow a first mover.	Shrinking markets, economic difficulties in incumbent industries, loss of confidence in existing technologies and business models, reorientation towards alternatives.
<b>Social</b>	Growing support coalitions and constituencies improve available skills, finance and political clout.	Disagreement and fracturing of social networks, defection of key social groups from the regime.
<b>Political</b>	Advocacy coalitions lobby for policy changes that support the niche innovation such as subsidies and supportive regulations.	Eroding political influence of incumbent industries, declining political support, removal of supportive policies, introduction of disruptive policies.
<b>Cultural</b>	Positive discourses and visions attract attention, create cultural enthusiasm and increase socio-political legitimacy.	Negative cultural discourses undermine the legitimacy of existing regimes (e.g. coal and climate change, diesel cars and air quality).

### **3. Socio-technical analysis of the German electricity transition (1990-2016)**

To make the socio-technical approach more concrete, we provide an illustrative analysis of the unfolding German electricity transition (Figure 3). Our aim is to illustrate the multiple economic, social, political and cultural processes at work, together with the interactions between the three levels illustrated in Figure 2. Our focus is the transition towards renewable energy technologies (RETs) that occurred over the period 1990-2016, which laid the foundation for the official energy transition policy (*Energiewende*) adopted in 2011.

Figure 3: German electricity generation by source, 1990–2016 (TWh)



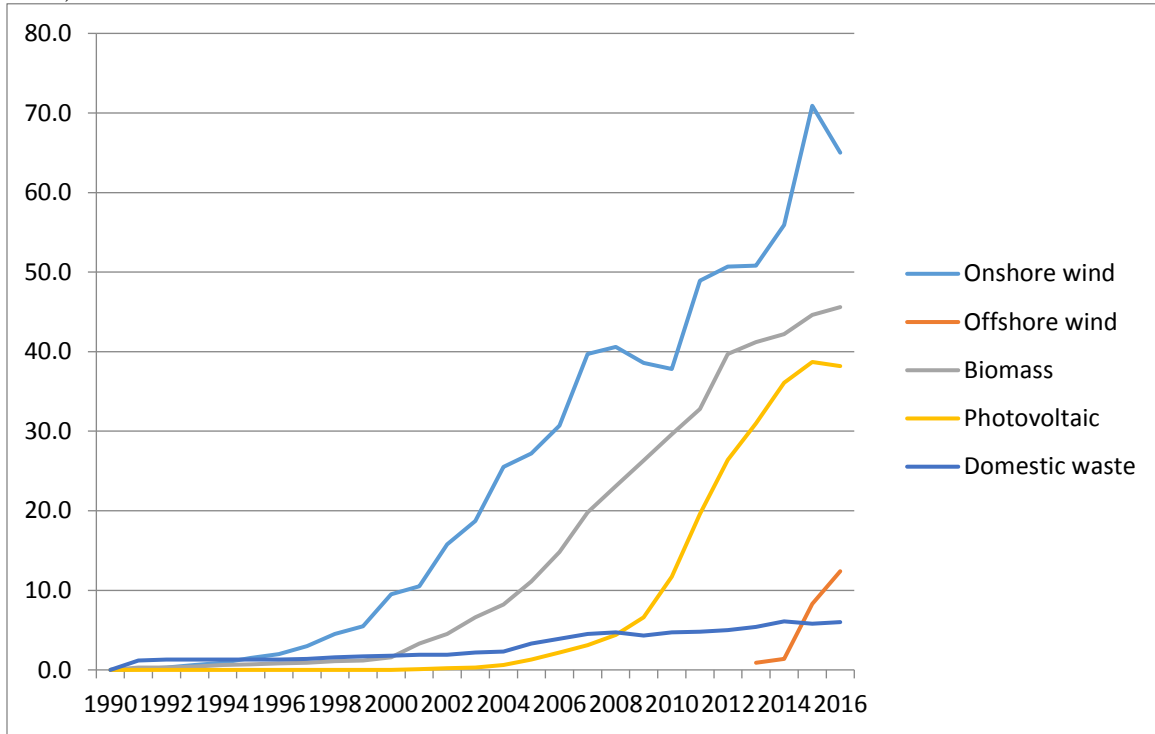
Source: AGEnergiebilanzen

German R&D programs in wind and solar-PV were stimulated by the 1970s' oil crises, but deployment initially remained limited because of poor performance and high costs.<sup>16</sup> During the 1980s, small wind turbines were adopted to some degree by environmentally motivated citizen groups, farmers and smaller utilities, which in turn helped to stimulate a positive discourse around green energy.<sup>17</sup> The 1986 Chernobyl accident was a landscape shock that stimulated the engagement of anti-nuclear activists who wanted to demonstrate the feasibility of alternatives.<sup>18</sup> The accident also hardened negative public attitudes towards nuclear power, leading to an institutionalization of views that had been advanced by an active anti-nuclear movement in preceding years.<sup>19</sup> This discursive 'crack' in the regime was plastered over by successive Conservative-Liberal governments, who continued to support nuclear power.

The nurturing of RET-niches continued in the 1990s, most notably through the 1991 Feed-In-Law that obliged utilities to connect RETs to the grid and to purchase renewable electricity at 90% of the retail price. Earlier proposals for RET market support had been defeated in Parliament, but the 1991 proposal succeed 'by accident' as the government was preoccupied with German re-unification.<sup>20</sup> The Feed-in-Tariff (FiT) made onshore wind deployment economically feasible, stimulating significant deployment in the 1990s (Figure 4). The success of German turbine manufacturers (Enercon, Husumer Schiffswerft, Tacke) expanded the RET support coalition and attracted industrial policy support in the peripheral regions of Northern Germany. The FiT was too low, however, to make solar-PV and biogas economically feasible. Green NGOs, industrial firms (including Siemens) and the German Biogas Association lobbied for more support, based on the discourse of ecological modernization, but with limited direct success.<sup>18</sup> The green advocacy coalition was successful, however, in defeating a 1997 government proposal to reduce the feed-in tariffs, which utilities had lobbied for. Public protests by

environmental groups, solar and wind associations, metal and machine workers, farmer groups and church groups led to the rejection of the proposal by the German Parliament.<sup>16</sup>

*Figure 4: Electricity generation from German renewable energy technologies, excluding hydro, 1990-2016 (TWh)*



Source: AGEnergiebilanzen

The election of a Red-Green coalition government (1998-2005) was a landscape shock that disrupted the cozy regime-level relations between utilities and policymakers. In 2002, the government decided to phase-out nuclear energy - a move that was opposed by utilities in subsequent years. The government also introduced the Renewable Energy Act (EEG, 2000), which guaranteed fixed, premium payments for renewable electricity over a 20-year period, with the tariffs varying with the maturity of the technology. The Red-Green government also liberalized the electricity sector in 1998. Subsequent mergers and acquisitions resulted in the Big-4 utilities (RWE, E.ON, Vattenfall, EnBW) capturing 90% of the wholesale market by 2004. By the mid-2000s, instead of focusing on renewables, the Big 4 were investing in new coal- and gas-fired power plants to meet expected demand growth.<sup>21</sup>

Between 2005 and 2011, the share of renewables in total generation doubled from 10.0% to 20.1%, owing to generous feed-in tariffs, falling costs (especially for solar-PV), positive discourses and growing societal interest.<sup>22</sup> The very rapid diffusion of solar-PV after 2006 (Figure 4) was unforeseen and driven by tariffs that far exceeded the cost of generation. This stimulated strong interest from households who deployed small-scale rooftop PV systems, and from farmers who deployed large-scale roof- and field-mounted systems.<sup>23</sup> Despite having a relatively limited solar resource, Germany accounted for almost one third of global PV capacity by 2011. Solar-PV became an industrial success story, as total sales of the German PV industry grew from €201 million in 2000 to €7 billion in 2008. Export sales grew from €273 million in 2004 to approximately €5 billion in 2010.<sup>24</sup> The EEG also



enabled a ‘social opening up’ of the electricity sector<sup>18</sup>, with farmers, municipal utilities, households, communities, project developers, and other industries entering the generation market (Table 2). In contrast, incumbent utilities had only limited involvement in RET-deployment, producing only 6.5% of non-hydro renewable electricity in 2010 (Table 2).

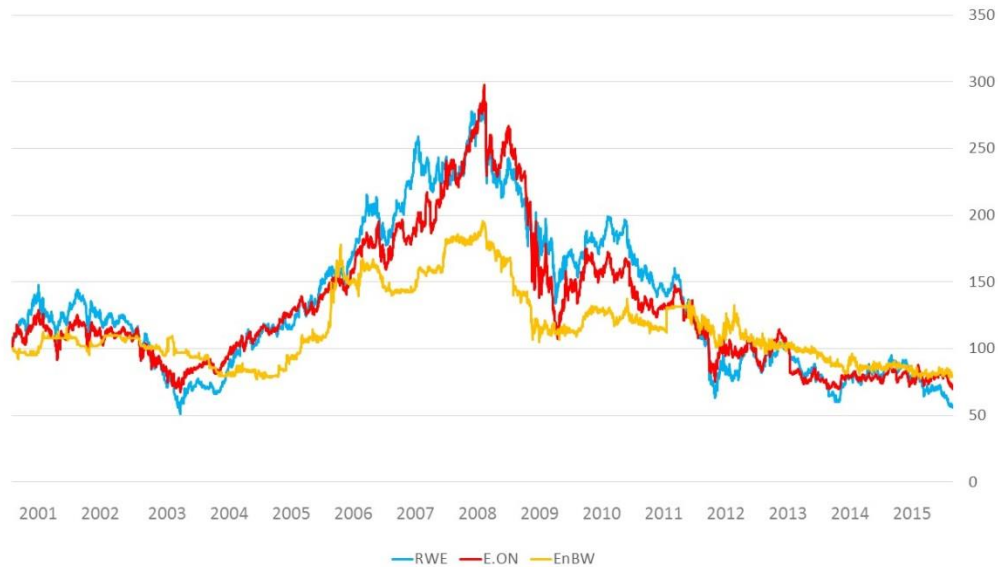
*Table 2: Ownership of installed capacity of different renewable electricity technologies in Germany in 2010 (%)*

	Households	Farmers	Banks, funds	Project developers	Municipal utilities	Industry	Four major utilities	others
Wind	51.5	1.8	15.5	21.3	3.4	2.3	2.1	2.2
Biogas	0.1	71.5	6.2	13.1	3.1	0.1	0.1	5.7
Biomass	2.0	0	3.0	6.9	24.3	41.5	9.6	12.7
Solar-PV	39.3	21.2	8.1	8.3	2.6	19.2	0.2	1.1

Source: Ref 25

The Big 4 utilities continued to focus on growth in this period, increasing their stock prices (Figure 5) through European and global expansions.<sup>26</sup> They also enjoyed windfall profits from the European Emissions Trading Scheme (EU ETS), since they were allowed to raise wholesale prices to reflect the opportunity cost of carbon allowances, despite receiving those allowances for free.<sup>27</sup> After years of lobbying, the utilities also scored a political victory when the newly elected (2009) Conservative-Liberal government decided to overturn the earlier nuclear phase-out decision. Their public reputation deteriorated towards the end of the decade, however, because they were increasingly seen as large oligopolists that faced insufficient competition, generated excessive profits and ignored public concerns. After 2008, the utilities faced growing economic pressures from the financial crisis (which depressed economic activity and thereby electricity demand), the expansion of renewables (which reduced the market share of fossil plants), and decreasing wholesale electricity prices (because of declining coal prices and low marginal costs of renewables, which means they are dispatched first in power generation). These developments led to a decline in net income from 2011 onwards.<sup>26</sup>

Figure 5: Share price performance of German electricity companies normalized by starting date\*



Source: Finanzen.net. \* Note: Vattenfall is not included because it is a Swedish state-owned company.

The 2011-2016 period saw the destabilization of the electricity regime and further diffusion of RETs, which accounted for 29% of electricity generation in 2016. The Fukushima accident (2011) was a landscape shock that led the government to perform a U-turn, and re-introduce the nuclear phase-out, with a target date of 2022. The government also introduced an economy-wide energy transition policy (*Energiewende*) that included ambitious targets for renewable electricity (35% by 2020, 40-45% by 2025, 55-60% by 2035 and 80% by 2050). Regime destabilization thus created opportunities for the diffusion of renewables, as predicted by the MLP. Diffusion was also driven by endogenous dynamics, such as policy support, positive discourses and declining RET-prices. The price of PV-modules, for instance, decreased more than 65% between 2007 and 2011, as a result of scale economies in Chinese production, oversupply, and price-dumping.<sup>28</sup> Growing market demand boosted German solar-PV generation, which increased from 6.6 TWh in 2009 to 38.2 TWh in 2016 (Figure 4).

But these developments also had unintended negative consequences. For example: 1) many German PV-manufacturers went bankrupt because of Chinese competition, which eroded the strength of the green growth discourse; 2) renewables deployment (especially solar-PV) increased EEG-surcharges from 1.3 eurocent/kWh in 2009 to 6.24 eurocent/kWh in 2014, helping to make German retail electricity prices the highest in Europe;<sup>22</sup> 3) the growing size and regressive nature<sup>29</sup> of these surcharges encouraged political opposition, including from utilities and the Economics Ministry; and 4) the growing proportion of intermittent renewables threatened grid stability and increased wholesale price volatility in both German and neighboring electricity markets - with negative prices on sunny, windy days when supply exceeded demand.

These problems led to government efforts to contain the speed and direction of the electricity transition. Cost-reduction attempts from 2010 onwards led to several downward adjustments in the EEG-policy.<sup>30</sup> The substantial 2012 adjustment in EEG subsidies sharply slowed solar-PV deployment (Figure 4). Another adjustment in 2014 announced that feed-in-tariffs would be replaced by a bidding system for target capacity by 2017, which is likely to introduce more uncertainty. To facilitate market

integration of RETs, the government introduced new policies to stimulate direct marketing of renewable electricity.<sup>31</sup>

Another reason for introducing these containment policies was that the Big-4 utilities were facing substantial economic problems. The immediate shut-down of eight nuclear reactors in 2011, and the closure of the remainder by 2022, threatened major financial losses. Low wholesale prices and competition from RETs undermined the profitability of many conventional power plants, leading to doubts about the viability of traditional business models. In 2012, the CEO of EnBW stated in the annual report that: "...I see a paradigm shift in the energy sector that questions the traditional business model of many power supply companies." A confidential paper titled 'RWE's Corporate Story' raised gloomy prospects: "...The massive erosion of the wholesale prices caused by the growth of German photovoltaics constitutes a serious problem for RWE which may even threaten the company's survival."<sup>22</sup> In this volatile context, Big-4 utilities began strategic reorientation activities, searching for viable business models. In 2014, E.ON decided to split its business into two separate companies: one would focus on renewables, distribution grids and service activities, the other would hold conventional assets in large-scale electricity production and trading activities. In 2015, Vattenfall offered its German lignite activities for sale, which represented a major retreat from the German market. In 2015, RWE announced plans to separate its renewables, grid and retail business in a new subcompany.<sup>26</sup> These problems raised concerns in government, which perceived the utilities as 'too big to fail'. The government therefore aimed to slow RET-expansion and to strengthen support for the utilities. Conventional power plants were increasingly framed as complementary to RETs and as necessary (in the short to medium-term) for guaranteeing the stability of the electricity system. Attention also turned to new policies like demand-side response and 'capacity markets', with the latter rewarding generators for providing available capacity rather than electricity generation.<sup>31</sup> The government also stimulated the deployment of offshore wind, which provided an attractive diversification opportunity for incumbent utilities because of size and cost structures.

This brief case study demonstrates several core themes of the socio-technical perspective. First, the German energy transition was clearly a multi-dimensional process, with complex interactions between techno-economic, business, social, political and cultural dimensions whose relative importance changed over time.

Second, the transition can be fruitfully analyzed as struggles between niche-innovations (linked to new entrants) and existing regimes (linked to incumbents). Exogenous landscape pressures (Fukushima, financial-economic crisis) played important roles in destabilizing the regime and creating windows of opportunity for the diffusion of niche-innovations. The success of niche-innovations also depended upon endogenous drivers, such as supportive policies, price/performance improvements, new business creation, positive discourses and broad advocacy coalitions.

Thirdly, the transition was non-linear and characterized by surprises. For example: 1) the solar-PV boom after the mid-2000s was not foreseen; 2) the green growth success story was disrupted by cheaper Chinese imports that bankrupted several German firms; 3) the Fukushima accident was an influential external shock that triggered a policy U-turn; and 4) the expansion of intermittent renewables disrupted normal market functioning, creating the need for fundamental redesign. Such non-linearities and surprises are common in transitions, implying that policymaking needs to be flexible and adaptive.

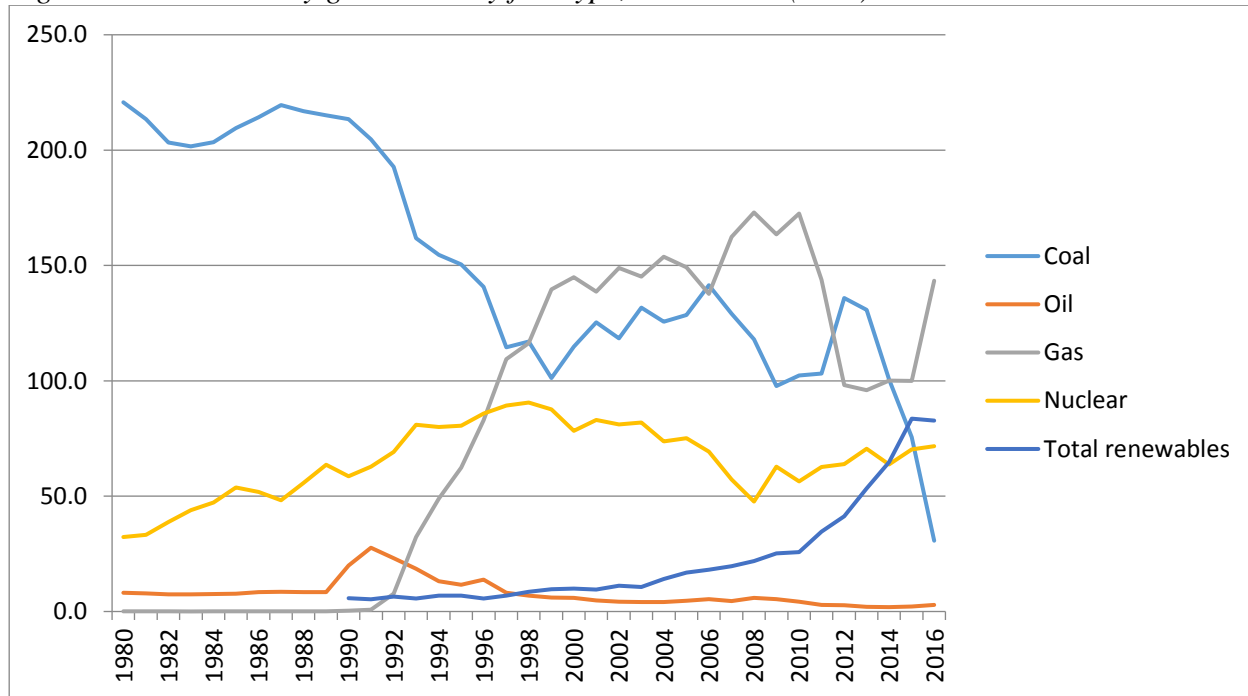
Fourthly, the transition was full of political conflict and struggles. There were continuous struggles, for instance, over nuclear policy. Utilities fought the 2002 phase-out decision, lobbied the Conservative-Social Democrat government (2005-2009) for a roll-back, succeeded in 2009, were faced

with a U-turn in 2011 and have since sought financial compensation for the nuclear phase-out via court cases. There were also struggles between Ministries over responsibilities and priorities. In 2002, for instance, the Red-Green government transferred the responsibility for renewable energy policy from the Economics Ministry to the Ministry for Environmental Affairs, which was more positively oriented towards RETs. In 2014, the government transferred this responsibility back to the Economics Ministry. Another battleground was the resistance from German utilities against renewables support policies. In 1995, utilities contested the legality of the Feed-In-Law in German courts and the European Court of Justice. They also tried to delegitimize RETs by framing them as expensive and unreliable. Since 2009, this discourse gained traction with Conservative-led government coalitions. Combined with concerns over the economic viability of utilities and the impact of rising prices on electricity consumers, the government started downscaling EEG-support. This last point also highlights the importance of dealing with potential ‘losers’ in transitions, something we address further below.

#### 4. Status of low-carbon transitions in different domains

Broadening out from this case study, we use the MLP to briefly appraise the status of low-carbon transitions in different domains. Progress is greatest in electricity systems, where niche-innovations like wind and solar-PV are diffusing rapidly<sup>32</sup>, moving from phase two to three in countries such as Denmark, Portugal, Germany (see Figure 3 above) and the UK (Figure 6). The result is substantial disruption of existing regimes (e.g. economic problems for utilities, threats to supply security) and major adjustments to those regimes (e.g. interconnection, electricity storage, smart grids, demand-side response, market redesign). However, other low-carbon innovations such as CCS and nuclear energy are progressing much slower than anticipated, owing to implementation problems related to public opposition, industry resistance and lack of political will.<sup>33</sup>

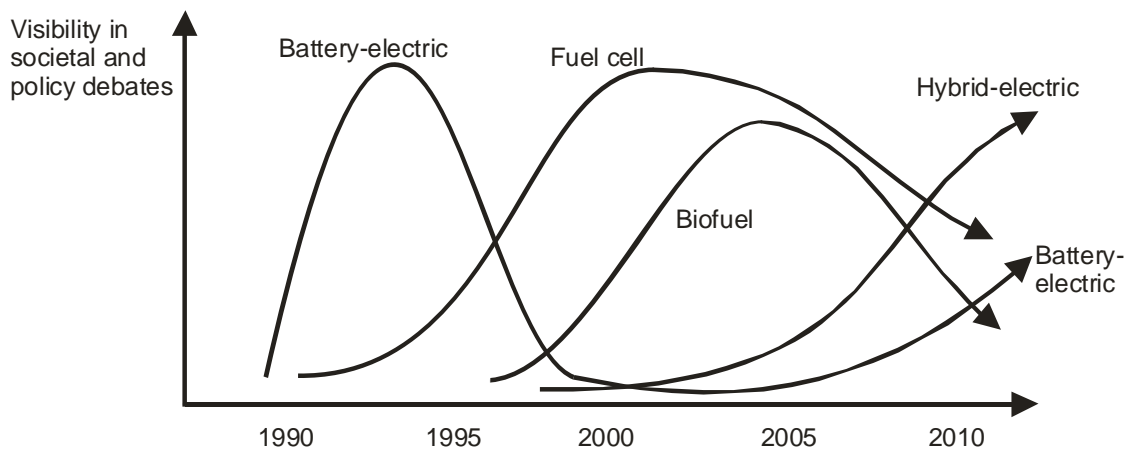
Figure 6: UK electricity generation by fuel type, 1990–2016 (TWh)



Source: Digest of UK Energy Statistics

Low-carbon transitions have less momentum in passenger transport, where the petroleum-fueled auto-mobility regime is still deeply entrenched in most Western countries. Some niche-innovations are moving from phase one to two, particularly hybrid-electric vehicles (HEV), plug-in hybrids (PHEV), and battery-electric vehicles (BEV). In 2015, more than 1.26 million PHEVs and BEVs were on the road globally, and they exceeded 1% of new vehicle sales in five countries (Sweden, Denmark, France, China, UK) and 5% in two more (Norway and the Netherlands).<sup>34</sup> In 2017 Volvo announced that it will cease production of conventional vehicles by 2019. However, while many analysts extrapolate these positive trends into the future, others are more cautious because low-carbon transport innovations have a history of hype-disappointment cycles (Figure 7).<sup>5</sup> It seems as if BEVs are currently experiencing a second period of hype, after an earlier one followed by disappointment in the 1990s. Then again, it is also possible that organizations such as the IEA will be proven correct and that a genuine breakthrough and accelerated diffusion of BEVs will take place in many countries over the next decade.

Figure 7: Hype-disappointment cycles for green car propulsion technologies



Source: Ref. 14

Low-carbon transitions in agriculture and food are also progressing slowly. Agriculture is a very dispersed regime (geographically and via commodity chains), with supermarkets and food processing occupying powerful positions between consumers and farmers. Low-carbon niche-innovations exist (e.g. artificial meat, organic food, manure digestion, farmers markets, vegetable box schemes), but have limited momentum because of high costs, cultural attachments to existing diets, weak and fragmented policies, and industry reluctance.<sup>35</sup>

Heat and building regimes are also fairly stable owing to the slow turn-over of stock, the high cost of low-carbon alternatives, industry lock-in and entrenched user practices. Incremental innovations (efficient boilers, insulation, double glazing) have improved the energy performance of buildings but opportunities for further deployment are declining. In contrast, radical niche-innovations, such as whole-house retrofits, passive houses, heat pumps and district heating networks have relatively little momentum and continue to face multiple obstacles such as high upfront costs, split incentives, limited consumer familiarity, absence of supporting infrastructure and limited supply chain skills.<sup>36</sup>

One reason for the more rapid transition in electricity is that the relevant technologies are easy to target and policies like feed-in-tariffs have been highly successful in reducing investment risk. However, this begs the question of why similar policies have not worked as well in other systems. We suggest that the electricity system has three characteristics that facilitate more rapid transition. First, the electricity grid acts as a buffer, making it possible to make radical changes to the generation mix with only limited consumer involvement. Consumers typically pay for low-carbon electricity generation through their electricity bills, but many are unaware of this indirect involvement mechanism. This is different in food, mobility, heat and buildings, where consumers need to actively decide to purchase low-carbon innovations, which are often costly and have different functional characteristics. Second, electricity is an undifferentiated product, meaning that consumers do not experience changes in functional characteristics with low-carbon electricity and do not need to change their practices. Again, this is not the case for mobility, food and buildings. Third, it is easier for policymakers to interact with a few centralized oligopolistic utilities than with millions of farmers, installers or small building companies (although countries like Germany and Denmark are counter-examples in the electricity sector). But despite these differences in system characteristics, meeting ambitious climate targets requires accelerated transitions in all sectors. This in turn, requires more differentiated policies, which we address next.

## 5. Lessons for managing low-carbon transitions

Governing low-carbon transitions is complex, because of *uncertainties* (about the future price and performance of radical innovations, social acceptance, consumer interest, policy support), *disagreements* (about desirable solutions, policies, costs and benefits) and *distributed power* (policymakers are not all-powerful and depend on other actors).<sup>37</sup> It is therefore insufficient to rely solely upon technically rational criteria for decision-making, in which experts use computer models to determine an ‘optimal’ transition path which is then implemented by policymakers. Our socio-technical approach to low-carbon transitions highlights at least four important lessons for low-carbon policy.

### Focus on policy mixes, not isolated instruments

With regard to policy instruments, a sociotechnical approach reinforces the argument that policymakers should not rely exclusively upon single policy instruments - particularly carbon pricing which continues to face major political obstacles.<sup>38</sup> Instead, policymakers should mobilise a range of policies, such as financial instruments (taxes, subsidies, grants, loans), regulatory instruments (standards, laws, performance targets) and processual instruments<sup>39</sup> (demonstration projects, network management, public debates, consultations, foresight exercises, roadmaps). The appropriate mix is likely to vary between countries and domains, depending on political cultures and stakeholder configurations.<sup>40</sup> Even in Germany, the success of a ‘demand-pull’ instrument such as the feed-in tariffs only worked as well as it did because it formed part of a broader policy mix including ‘supply-push’ mechanisms such as subsidies for research and ‘systemic measures’ such as collaborative research projects and systems of knowledge exchange.<sup>41</sup>

As a general strategy for managing transitions, it is best to first nurture low-carbon niche-innovations and support coalitions and then to enhance selection pressures.<sup>38 42</sup> Concretely, in phase one and two of transitions, policymakers should prioritize processual and innovation support policies (e.g. demonstration projects, foresight and scenario workshops, R&D subsidies, feed-in tariffs), aimed at creating ‘protected spaces’ for niche innovations that encourage learning, network building, initial

deployment, and articulation of visions and discourses.<sup>43 44</sup> In phase three, when niche-innovations have acquired internal momentum, policy-making should become more selective by increasing pressures on the regime via economic incentives (e.g. carbon-pricing) or stricter regulations. The niche-related support coalitions, which were built in phase one and two, may help counter the political resistance and fight-back from incumbent actors in phase three.<sup>4</sup>

### Analyze politics, in addition to policy

Because low-carbon transitions are inevitably political, scientists should provide analysis *of* policy (and politics) as well as *for* policy.<sup>45 46</sup> Political scientists have developed a number of theoretical models that both *explain* policy-making processes and provide useful insights for *influencing* those processes. For example, theories of *policy networks* see policymaking as a deeply political process involving negotiations, compromises and the building of coalitions with stakeholders.<sup>47</sup> Acknowledging disagreements and distributed power, politics is the ‘art of the possible’ rather than the ‘calculation of the optimal’. This suggests that more expensive transitions may be preferable if stakeholder support makes their implementation more feasible. To support policymakers, scholars could offer better analyses of the interpretations, interests, resources and strategies of different groups.<sup>48</sup> In other words, policy analysts should focus more on the complex dynamics involved in political struggles, social acceptance and governance, where factors can both serve as constraints or catalysts for accelerated transition.

Similarly, theories of *incrementalism*<sup>49</sup> and *muddling through*<sup>50</sup> see policy implementation as a process of improvisation, experimentation, and learning-by-doing. This is particularly appropriate for managing the non-linear development of radical innovations, which may lead to surprises and unintended consequences that require flexibility and adjustments. To support policymakers, scholars could offer better analyses of the determinants of success for niche-innovations, including the role of demonstration projects, network building and learning processes.<sup>43 44</sup>

### Broaden the solution space, beyond supply-side technology and economics

As noted, low carbon transitions are proceeding at very different speeds in different parts of the economy. These widely different outcomes are only partly linked to the relative cost of abatement in these different sectors, or to the specific characteristics of those sectors. They also reflect blind spots on the part of policymakers and analysts - which in turn are linked to the cognitive constraints imposed by existing regimes (restricting the perceived solution space), the inertia and path dependence of those regimes and the political influence of the relevant incumbents.

The most obvious example of this is the bias towards energy supply, rather than energy demand technologies - visible within energy R&D programs, deployment support programs, integrated assessment models and the overall policy mix.<sup>51</sup> Thirteen of Pacala and Socolow’s climate stabilization wedges, for instance, focus on supply; only two wedges address demand (reduced use of vehicles, efficient buildings).<sup>52</sup> Some reasons for this bias are<sup>51</sup>: energy supply technologies are small in number, similar in configuration, characterized by good data availability (which enables modeling) and provided by a small number of well-organized and politically powerful sectors. Large supply-side investments are also politically salient with straightforward evaluation metrics (e.g. £/kWh), lending themselves to targeted and dedicated policy support. In contrast, end-use technologies (washing machines, televisions, boilers, internal combustion engines, ICT devices) are large in number, diverse in configuration, focused primarily upon other services, and are supplied by a large number of sectors with less political power. The impact of efficiency improvements in those technologies (which have



been substantial in some instances, e.g. refrigerators and light bulbs) is largely invisible, and the systems in which they are embedded are more difficult to target through policy intervention. The net result is a relative neglect of demand-side opportunities within climate policy, despite their multiple social benefits<sup>53</sup> and the expectation that they will account for more than half of the total global carbon abatement over the next century.<sup>54</sup>

A second example is the bias towards technological solutions, rather than broader changes in individual routines and social practices - such as more cycling and walking, car sharing, eating less meat, extending product life and purchasing second-hand or used items. In combination, these have the potential to provide significant emission reductions.<sup>55 56</sup> But despite this potential, it remains difficult for policymakers to deliberately and substantially change user practices in low-carbon directions, for fear of being accused of being an interventionist ‘nanny state’.<sup>57</sup>

From a socio-technical perspective, approaches to stimulate end-use technologies or behavior change should go beyond the dominant individual perspective, which focuses either on changing prices or on information provision (e.g. telling people it would be good for the climate if they adjust thermostat settings, turn off unneeded lights, or operate washing machines at full-loads). The literature on technological domestication emphasizes that consumers do not just *buy* new technologies but also embed them in their daily lives, which entails *cognitive* work (learning about the artefact and developing new competencies), *symbolic* work (articulation of new interpretive categories and cultural conventions) and *practical* work (adjustment of user routines to match the new technology).<sup>58 59</sup> The literature on user practices also suggests that substantial behaviour change usually involves co-evolving changes in skills, meanings and material components.<sup>60</sup> Pricing and information strategies should therefore be complemented with policies aimed at learning (e.g. demonstration projects that address not just technical performance, but also users routines), public debates, and inclusion of trusted intermediary actors (e.g. consumer organizations, retailers, NGOs, community groups).<sup>61</sup>

### Actively manage phase-outs, in addition to stimulating innovation

Many analysts and planners emphasize the necessity of introducing niche-innovations, but this can obscure an equal need to phase-out existing, carbon-intensive regimes.<sup>62</sup> Such phase-out policies could include: 1) regulations that reduce emissions from specific technologies or sectors; 2) changing market rules for decarbonisation e.g. through a carbon tax or pricing; 3) policies to force social discussion and debate, such as the creation of new committees or networks; and 4) reduced support (such as tax breaks or subsidies) for high-carbon technologies.

The political resistance to phase-out is likely to be intense. Sovacool discussed different techniques for estimating global energy subsidies, showing that assessments range from \$1.9 to \$5.3 trillion (on a post-tax basis) per year, which mostly benefit coal, oil, and natural gas.<sup>63</sup> On the top-end, the International Monetary Fund (IMF), using an approach that monetized the ‘full social costs’, estimated that, in 2015, global fossil fuel subsidies amounted to \$5.3 trillion on a ‘post-tax basis’ equivalent to 6.5% of global GDP.<sup>64</sup> According to the IMF data, coal and petroleum still receive the lion’s share of these subsidies; with the largest subsidies in absolute terms being in China (\$2.3 trillion), the United States (\$699 billion), and Russia (\$335 billion). This means that the financial stakes of decarbonisation are vast— and the losers significant.

The potential job losses associated with displacing coal, natural gas, and oil may also lead to resistance. Some of these skills and jobs may be transferable to other sectors, such as offshore oil platform engineers putting their expertise into offshore wind turbine foundations, but many will not. A related concern is that higher income groups tend to be the first to adopt niche-innovations such as



solar panels, electric vehicles and zero-energy buildings.<sup>65</sup> Hence, subsidising those technologies could unwittingly exacerbate income inequality, especially if these subsidies are funded by levies on energy bills.

A pragmatic solution to managing, or at least ameliorating ‘losses’, is to actively plan for them, and then provide adjustment packages for those most harmed—an action that may also undercut some of the political opposition against decarbonisation (and one that could be funded by carbon pricing). In simple terms, losers need compensation so they will be less likely to hinder transitions. For instance, the German phase-out of coal subsidies involved a savings package for unemployed miners and subsidy reform packages introduced by Iran, Namibia, the Philippines, Turkey, and the United Kingdom provide similar compensating measures to affected groups.<sup>63</sup> Such efforts ensure that what is necessary to protect the climate is also just for the most vulnerable in society.

## 6. Conclusion

Techno-economic approaches in energy studies are crucial for analyzing and managing low-carbon transitions. But since transitions are disruptive, contested, and non-linear, they cannot be reduced to a technical deployment challenge. Nor are they driven solely by financial incentives, regulation and information provision. Low-carbon transitions also involve social, political and cultural processes, and changes in consumer practices. The multi-level perspective offers a big picture analytical framework that accommodates these broader processes and helps explain both stability and change. Energy and climate policy should not only include finance and regulation, but also stimulate learning and experimentation and the building of coalitions that develop emerging niche-innovations and support political struggles. Analysts and policymakers thus should look beyond single policy mechanisms such as carbon pricing and consider how a range of instruments can be woven into an effective mix. Analysts should also recognize that disagreement and contestation are central to low-carbon transitions and consider how best to accommodate these conflicts rather than ignore them. This will require aligning climate policy with broader policy objectives, minimizing the impact on low-income groups and providing explicit compensation. To understand and address these issues, techno-economic approaches should be complemented with frameworks that address the socio-technical dynamics of low-carbon transitions.<sup>66</sup>

### Author Contributions

F.W.G led the drafting of the text with inputs from all other authors. All authors contributed to the intellectual content.

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